Pulsed Synchrotrons for Very Rapid Acceleration

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Outline

- Introduction
- Lattice
- Magnet design
  - Goals
  - Iron properties
  - Latest design
  - Computation challenges
- Conclusions

Ordinary Synchrotrons

- Accelerating in an ordinary synchrotron
  - All magnetic fields increase in proportion to particle momentum
  - Closed orbit, tunes identical at every energy
  - Acceleration is sufficiently slow that either
    - The RF frequency can be adjusted as the time of flight varies, or
    - The beam adiabatically tracks the RF bucket center
  - Eddy current effects and losses (in magnet, coils, vacuum chamber) can usually be neglected

Rapidly Pulsed Synchrotrons

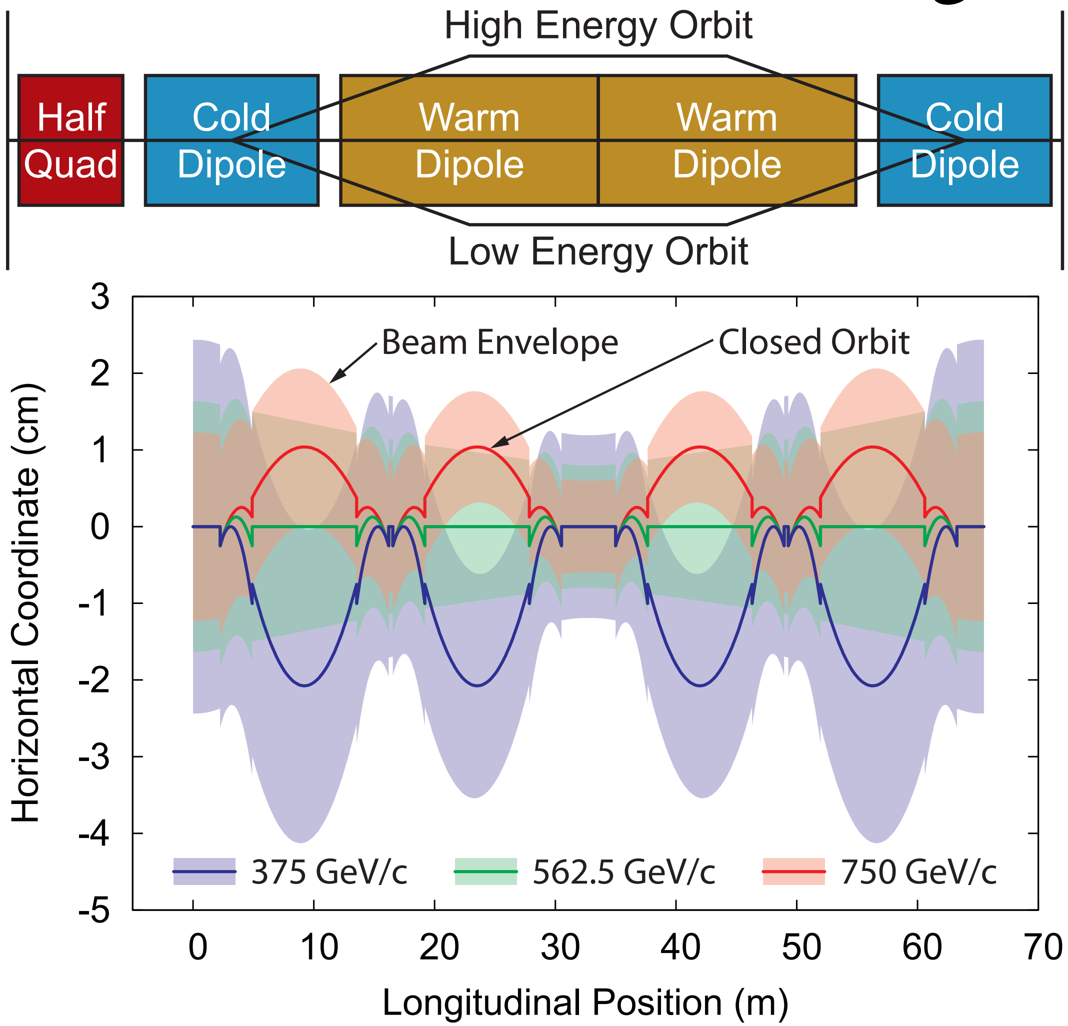
- Here we discuss rapidly pulsed synchrotrons
  - Cases where you are in a hurry to accelerate
    - Unstable particles, for instance
    - Requires high gradient (and therefore high frequency) RF
  - Time of flight varies more quickly than you can adjust the RF frequency. Beam will not adiabatically track the RF bucket center.
  - Eddy currents and losses are potentially significant
    - Losses in coils driving magnet
    - Additional losses in iron
    - Drive eddy currents in vacuum chamber

Hybrid Synchrotrons

- Field of pulsed magnets must be generated by iron
  - Too much stored energy if you use high field superconducting
- Limits bending field to roughly 2 T
- Would like a higher average bend field
  - More compact machine: important for both very high energies and machines for applications
  - When time is limited: need more RF for a longer ring
- Interleave superconducting fixed-field and bipolar pulsed dipoles
- Acts like a dipole with average field $(B_C L_C + B_W L_W)/(L_C + L_W)$

Hybrid Synchrotrons

- Beam will not remain centered in magnets



History

- First proposed by Summers in 1996
  - Subsequently discussed for other high energy accelerators
- Garren & Berg produced a lattice design in 2011, but with some items still to be addressed
- Summers built and tested magnets in 2012, demonstrating achieved field
- Witte created a dual-material dipole design in 2012

Hybrid Synchrotrons

- Given a desired acceleration rate:

$$L \propto \frac{p_{\max}(B_C + B_W) - p_{\min}(B_C - B_W)}{B_C B_W} \qquad n \propto L^{-1}$$

- Can get large momentum range, but most of ring dipoles are pulsed. Results in long ring.
- Reduce footprint with smaller momentum range, greater fraction of cold dipoles
  - Requires more stages; can potentially share tunnel
- High dipole fields important, particularly pulsed dipoles

Time of Flight Correction

- Time of flight varies with momentum
  - Not just velocity: beam motion in dipoles
- Insufficient time to re-phase RF
- Must correct time of flight
- Closed orbit will move off-axis in quadrupoles, sextupoles
  - Reduces average bend field
  - Can arrange dipoles relative to quads so that quads help bending
- Tighter interleaving of dipoles helps
  - Also reduces magnet aperture, power required
  - Inter-magnet spacing reduces efficiency

Muon Collider Example

- Magnets: 10 T fixed, 1.5 T pulsed

Hybrid	p_{min} GeV/c	p_{max} GeV/c	Time ms	Turns
No	63	375	0.3	10
Yes	63	173	0.1	18
Yes	173	375	0.2	18
Yes	375	750	0.4	18
Yes	750	1500	0.8	18

Pulsed Synchroton: Lattice Design

- Interleaved arc cells and linacs
- Maintain constant tune through acceleration
- Zero dispersion in linacs
- Correct global chromaticity (collective effects)
- Maintain high synchrotron tune (collective effects)
- Reduce beam excursion
- Have sufficient longitudinal acceptance
- Have sufficient accelerating gradient
  - Energy is discrete, magnet fields are continuous
  - Matches, tunes, etc. will not be exact
  - Want as many acceleration steps as is reasonable
  - Compact arc cells

Pulsed Synchrotron: Arc Cell

- Unit cell with arc and linac
- Minimum amount of bend per cell to create
  - First-order achromat
  - Cancellation of sextupole geometric nonlinearities
- Arc is 2π achromat with four $\pi/2$ FODO cells
  - D quads on ends to minimize horizontal orbit excursion
  - 3 sextuple families to correct
    - Chromaticity for full cell
    - Second-order dispersion
- Linac has 3 internal quads, different from arc quads
  - Permits variation of cell tune

Cell:

FL2/2	RF	DL	RF	FL1	RF	DE	B	F	B	D	B	F	B	D/2

Arc:

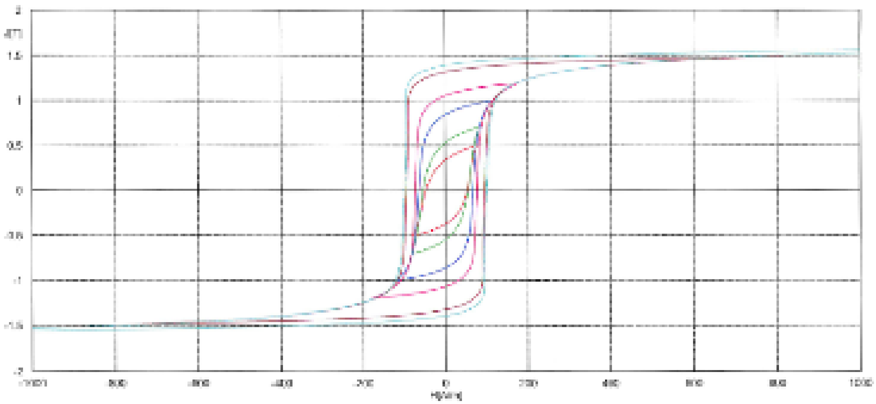
D/2	SD1	B		F	SF	B	SD2	D	SD2	B	SF	F		B	SD1	D/2

Magnet Design Principles

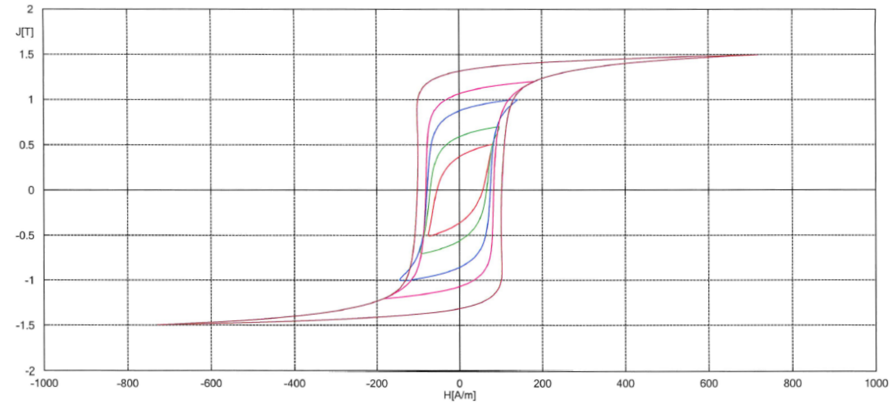
- Want high field
- Pulsed, so need to watch losses: iron and coils
- Coil losses: I^2R and eddy current
  - Reduce I^2R losses: distribute current over a larger area
  - Longitudinally transpose cable strands
- Three types of losses in iron
  - Hysteresis: per pulse, only a weak function of frequency
    - Can also get worse with very thin laminates
  - Eddy currents:
    - Better with higher resistivity
    - Increases with frequency
    - Better with thinner laminates
  - Excess losses: eddy currents at grain boundaries?

Hysteresis Curves

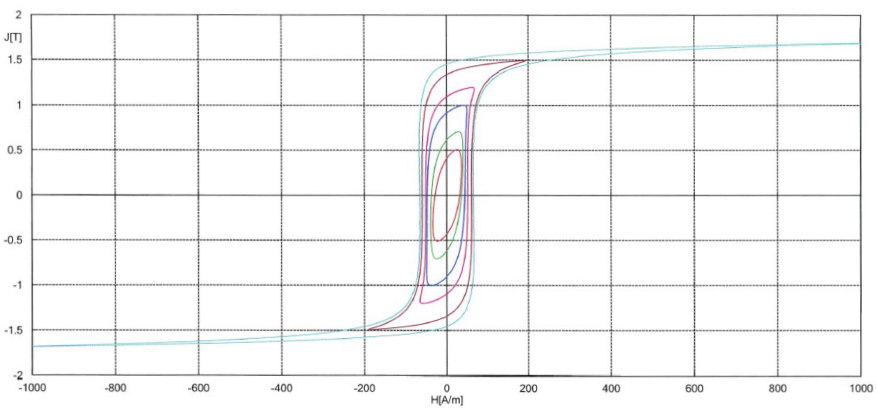
0.1 mil, 400 Hz



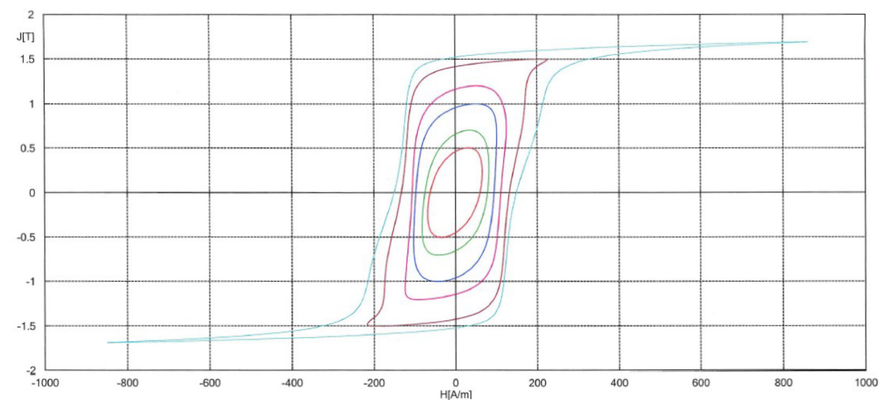
0.1 mil, 2000 Hz



0.6 mil, 400 Hz



0.6 mil, 2000 Hz



Arnold Magnetic Technologies, grain oriented steel sheets

Iron Parameters

Material	Resistivity $\mu\Omega\,\mathrm{cm}$	Dipole Field T
Pure Iron	10	1.75
3.5% Si Steel	40	1.55
3.5% Si Steel, GO	50	1.8
6.5% Si Steel	82	1.4
Fe-Co	44	2.0

Material Choice

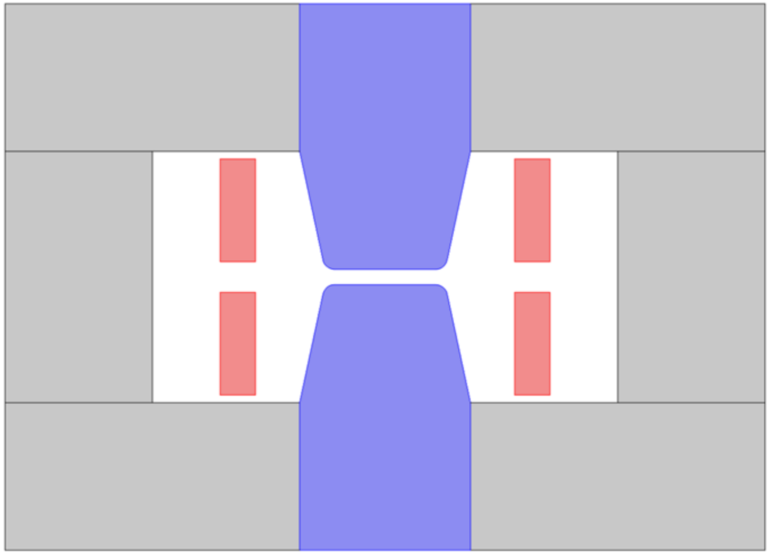
- Fe-Co is great, but Co activation a concern (but possibly manageable)
- Grain oriented steel almost as good, but
    - Field quality issues, since field lines pinned along grains
        - Assembly and stamping tolerances
        - Systematic variations in material properties
    - Simulations don’t converge for the nonlinear case, so no way to compute requirements
        - But recent positive results (WG2 talk, B. Cowan, Tech-X)
    - Unclear how to obtain permeability tensor needed for simulations

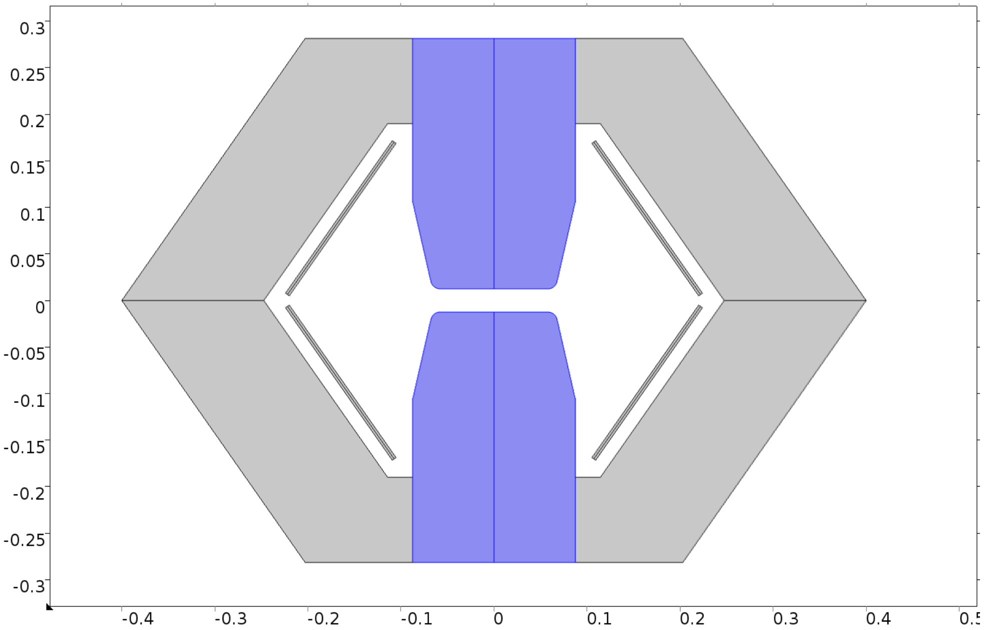
Material Choice

- Pure iron good field, but low resistivity: potentially high losses
  - Good material (VACOFER S1) only at largish thicknesses (200 μm), more eddy current losses
- 6.5% Si steel very low losses, but lower field
- 3.5% Si steel a good compromise, the usual choice
- We propose a hybrid design
  - Pole in 3.5% Si steel for higher field
  - Back yoke in 6.5% Si steel for low losses

Updated Magnet Design

- Changed geometry to reduce eddy current losses
- Stray field primarily from gap
- Long edge of coil apprximately parallel to field lines
- Reduces peak current density





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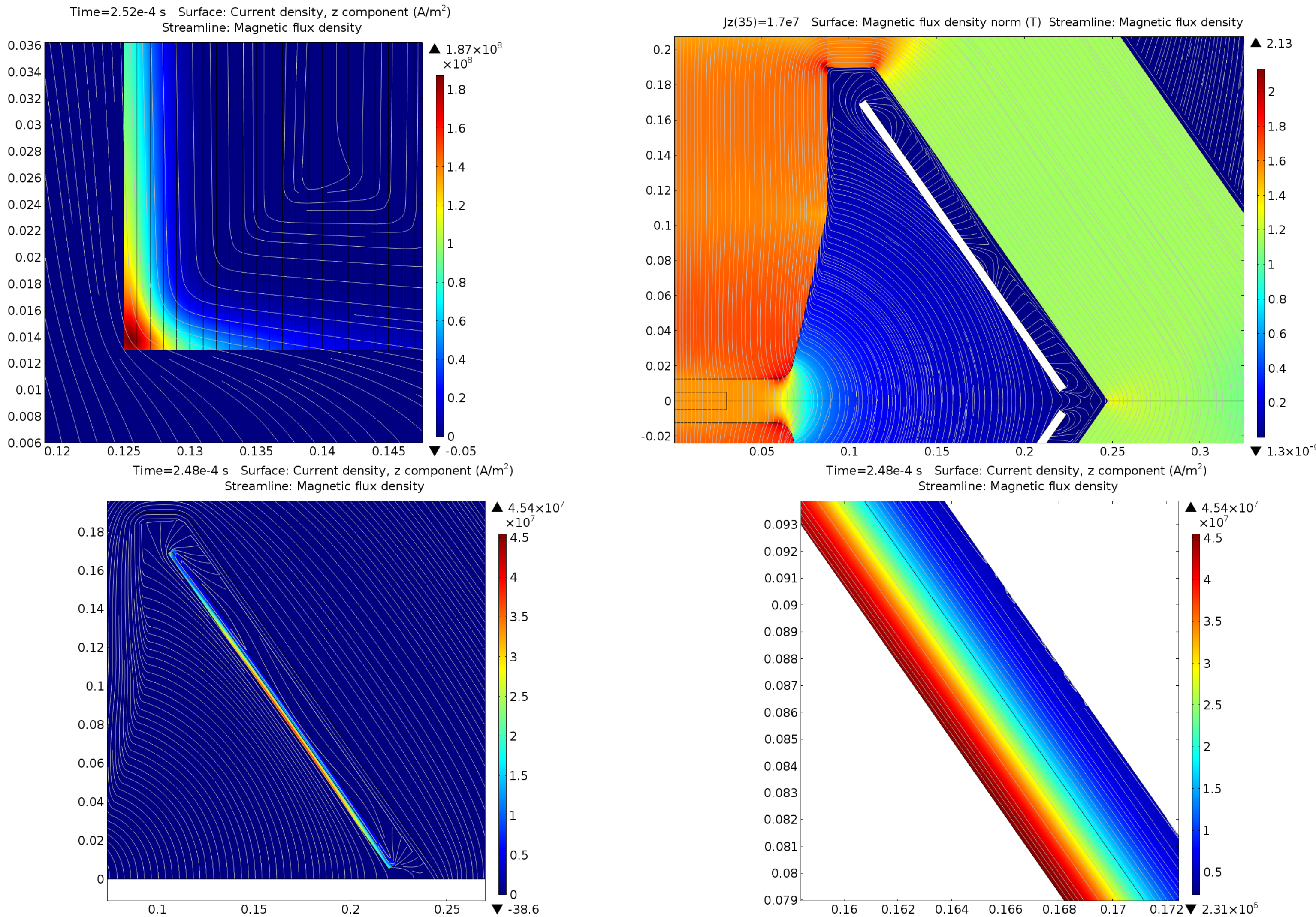
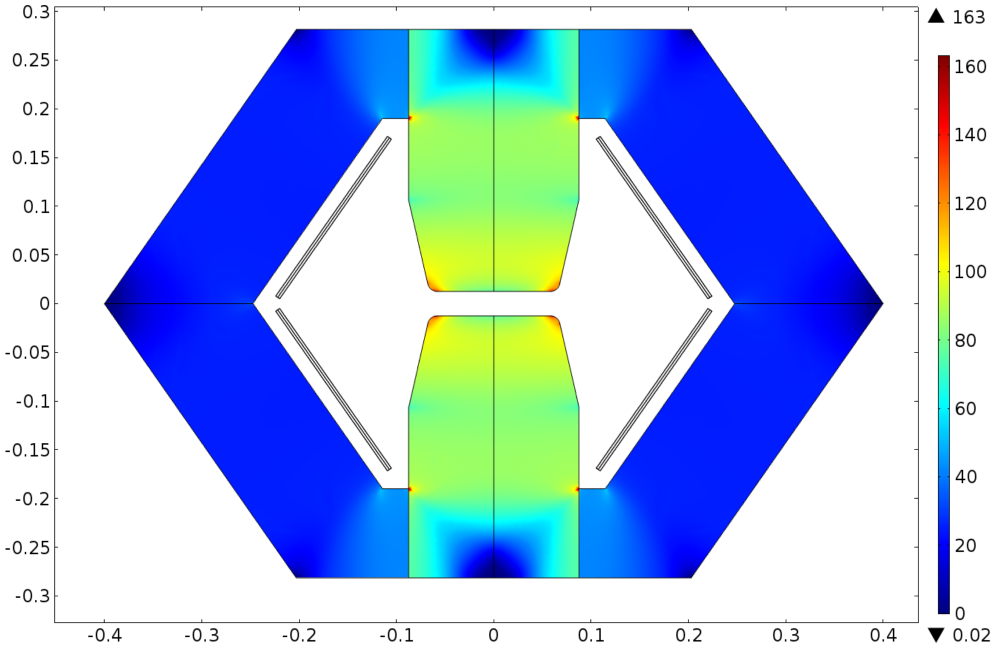
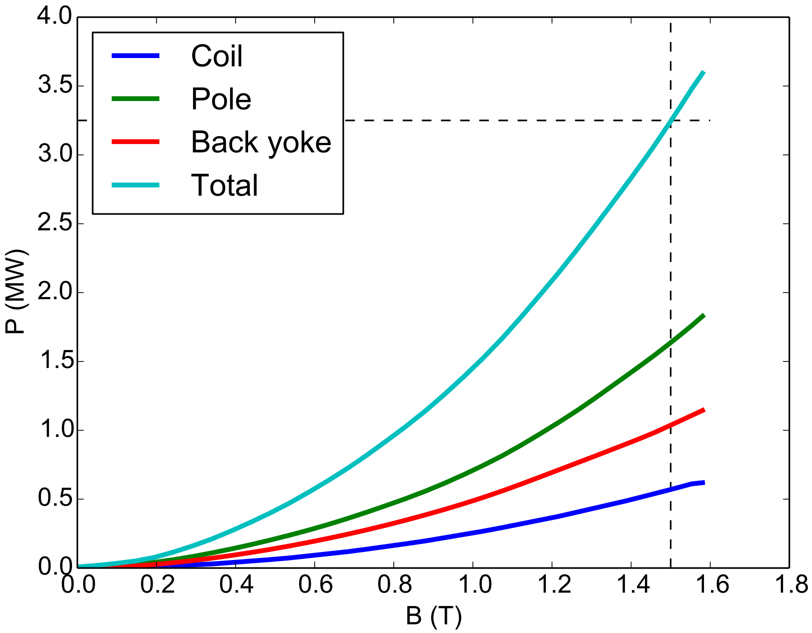
Updated Magnet Design



Overall Losses

- Losses dominated by pole
- 6.5% Si steel significantly reduces back yoke losses
- Eddy current losses in coil even smaller
  - Could be reduced further by transposing cable strands





Magnets: Computational Challenges

- Mostly centered around nonlinear B-H curves and poor convergence
  - Any simulation of grain oriented steel
  - Hysteresis simulations of non-oriented steel when going into saturation. Would probably drive into saturation to get linear rise when operating
- Size of problem when going into three dimensions
  - End effects
  - Longitudinal transposition of cable strands

Magnets: Computational Challenges

- Importance of computations
  - Designing for field quality while pushing field limits
  - Having a reasonable estimate of power losses
  - Linearity of drive-to-field response
- Having correct response curves for materials needed as input
  - Our concerns are different from usual high-frequency iron users
  - They care mostly about power, we care about field strength and details of the field distribution at high field
  - We would like to do a cost-benefit analysis for some interesting materials (e.g., high-purity iron)

Conclusions

- Hybrid pulsed synchrotrons allow rapid, efficient acceleration with a relatively compact machine
- Beams moving far off-axis as fields vary is a unique lattice design process
- High field and low losses are key criteria for magnet designs
- Have pulsed dipole designs with manageable losses
- Understanding iron properties is important for optimizing magnet designs
- Some questions we have expose limitations in magnetic simultaion codes

Future Directions

- Picking lattice parameters for a muon collider acceleration chain
- Choosing a good design for time of flight correction
- Measurement of necessary properties of magnet steel
- Improving magnet simulation code behavior for nonlinear magetization curves
- Large scale simulations of some 3-D effects
- Making a first pass at a power supply design
- Studying quadrupole and sextupole designs